THE PENNSYLVANIA STATE UNIVERSITY
DEPARTMENT OF GEOCHEMISTRY AND MINERALOGY
UNIVERSITY PARK, PENNSYLVANIA

Study of Structural and Mineralogical Significance of Meteorite Impact Sites, Including Mineral Paragenesis, High Pressure Polymorphs, Microfractures and Quartz Lamellae.

Fourth Semi-annual Report (January 1965 - June 1965)

to

National Aeronautics and Space Administration

Washington 25, D.C.

Grant No. NSG-473.

O. F. Tuttle

D. P. Gold

B. Robertson

F. K. Aitken

P. J. Wyllie

V. Vand

June 1965

TABLE OF CONTENTS

SUMMARY

Orientated specimens have been collected from and around a number of craters in granitic terrain. The craters include: Brent, Ontario; New Quebec and Lac Couture, Northern Quebec; Kofels, Austria; the Pretoria Salt Pan and the central granite dome of Vredefort in South Africa, and represent a range in diameters from 1 to 70 km. No further collections are anticipated.

Studies on the petrology and macro-structural features now are complete for the Lac Couture area. The area is underlain by gneisses, which vary in composition from granite to granodiorite, and which belong (with some variations) to the almandine-amphibolite facies of regional metamorphism. Retrograde metamorphism is evidenced by the conversion of biotite to chlorite and muscovite. The gneisses are thrown into broad concentric folds plunging from 10° to 60° south-southeast. Two sets of diabase dikes, striking respectively 105° and 135° cut the gneisses without deviation. Late hydrothermal veins composed largely of epidote are ubiquitous. The circular depression of Lac Couture is clearly a superimposed structure and is apparently underlain by a breccia pod. Glacial erratics of polymict breccia are present only on the western side of the lake, and are classified as comminuted rock matrix breccias and breccias of crypto- and/or microcrystalline matrix. Though no coesite nor stishovite has been detected in these breccias they are interpreted as being of the impact variety because of the presence of deformation lamellae in both quartz and feldspar.

Structural analysis of the primary foliation and the 'b' lineation substantiate the air photo interpretation (see 2nd Annual Rept.), and show a dominant foliation strike of 170° with steep dips, and a 'b'

lineation plunging approximately 60^{o} south-southeast, with a second maxima plunging approximately 10^{o} north-northwest. This suggests there is a second generation of gentle east-northeast trending folds.

Because of the absence of a topographic rim the surrounding area was divided arbitrarily into annular zones each representing a radius increment of 1 mile. A method for detecting undulations in the secondary structural features is applied to the sheeting joints, which have an essentially horizontal attitude in the country rock. The sheeting joints in the inner zone, which extends from the lake centre to 1 mile beyond the inner ring of islands, have a subhorizontal attitude. For the second zone (1 mile out from the inner zone) the sheeting joint attitudes have an annular distribution, suggestive of either a fossil rim or rim syncline. Successive zones outward conform to the country rock pattern. The subvertical joint planes have a more homogeneous pattern in the precints of the crater than they do farther out.

In order to discern possible strain effects in the solid state, the degree of undulose extinction in quartz was measured as a function of distance from the crater. No systematic variation was found. However, the mean extinction field of 12.3^{o} for quartz in the country rock was greater than the mean of 8.9^{o} for the breccias. This implies that some of the inherent strain is released by fracturing (shattering) during crater formation.

Variation in the optic angle (2V) and triclinicity of potash feldspar in a sample profile outward from the crater and in the breccias showed no variation. However in four cases 2V's varying from 32^{o} to 38^{o} were measured in the breccias. As yet their structural state is unknown.

Triclinicity values of potash feldspar around the New Quebec crater vary from 0.88 to 0.97, with no observable systematic variation outward from the rim.

The absence of structural state deformation in the rim and country rock suggest either an extremely rapid dissipation of energy outward from the explosion site or a dissipation of energy as brittle fracture (shattering) rather than elastic and plastic strain.

Library research on the feasibility of obtaining a quantitative measure of strain by integrating the stress induced glow curve (produced by thermoluminescent techniques), and plotting this as a function of distance from the crater, though not encouraging at this stage, requires further testing.

The detection of coesite and stishovite in rocks from environments of high stress concentrations continues to be negative.

PERSONNEL

The principal investigators were Professors O. F. Tuttle and D. P. Gold, with Professors V. Vand and P. J. Wyllie available for consultation. Dr. Tuttle directed the project, while Dr. Gold co-ordinated the research projects and compiled the results. Mr. B. Robertson, a graduate assistant, has almost completed a thesis on the 'Petrology of the Bedrock and Breccia Erratics in the Region of Lac Couture, Quebec'. He intends to submit this for the summer commencement in September 1965. Mr. F. K. Aitken, a graduate assistant, has investigated the feasibility of using thermoluminescence techniques for measuring strain in rocks, and also the structural state of feldspar crystals in and around the craters.

Dr. Gold returned recently from an approximately three month collecting visit to Africa. His itinerary included the crater fields of Rubirizi, Katwe, and Fort Portal in Western Uganda; the Tororo-Mt. Elgon Area in Eastern Uganda; the Homo Bay area in Western Kenya; Mts. Menengai, Longonot, and Suswa in the Eastern Rift Valley, near Nairobi, Kenya; the Pretoria Salt Pan and the Vredefort Dome in South Africa.

STRUCTURAL STUDIES AROUND THE LAC COUTURE CRATER

An account of the regional structure as deduced from the control traverses and an analysis of the aerial photographs is given in the Second Annual Report. The regional folds are concentric in type, plunging from 10° to 65° in a south-southeasterly direction.

A contoured π-plot of the attitudes of foliation and gneissic banding (plate 1, figure 1) shows a maximum, striking 170° and dipping steeply to east and west, with two partially developed girdles striking 080° - dip 10° south, and 065° - dip 60° southeast respectively. The girdles represent the areas of maximum curvature of respectively gently and steeply plunging domains of folds.

A contoured point diagram of the lineation (drag fold axes, long axes of rod, boudins and schlieren, and mineral elongations) shows an incomplete girdle with a maximum plunging about 55° in direction 150°, with secondary peaks plunging 85° south-southwest and 10° in direction 340° (see plate 1, figure 2). This spread suggests there has been gentle cross-folding on an east-northeast axis.

It was noted in the Second Annual Report that subhorizontal sheeting joints were ubiquitous and that nearer the lake some flexed sheeting planes were observed. In order to pick up possible annular folds (using sheeting joint planes as a control), the area surrounding the lake was divided into concentric zones, the first or inner zone covering the islands with each successive zone (up to zone 6) each a mile farther out. The results are plotted on plate 2. The plots for zones, 3, 4, & 5 were so similar that they were grouped together. The subhorizontality of the sheeting joints for zone 1, zones 3, 4, & 5, and zone 6 are demonstrated in figures 1, 3, & 4. However, for zone 2

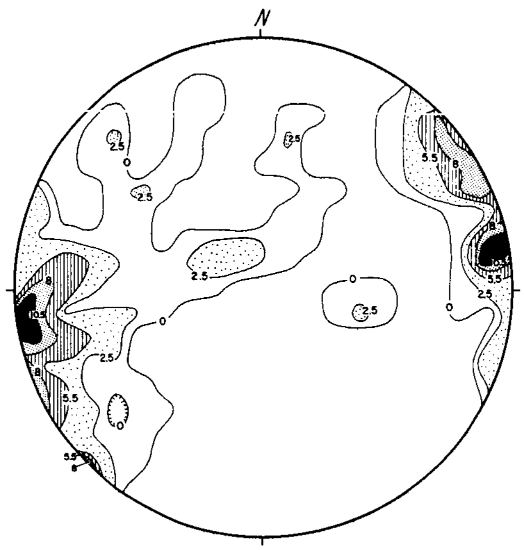
Lac Couture Crater

Plate 1.

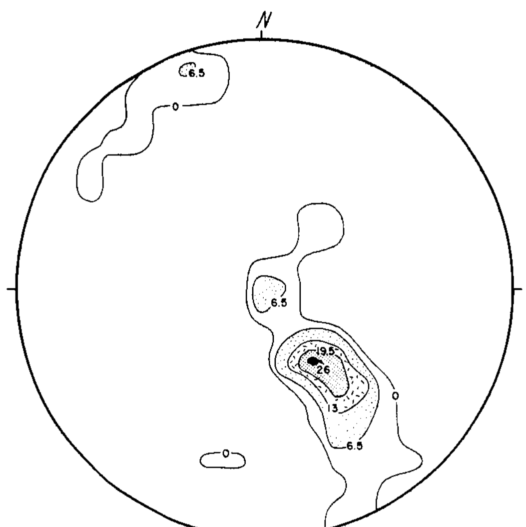
FIGURES

1. π-diagram of foliation and gneissic banding for the Lac Couture area. (Contoured by the Schmidt method).

2. β-diagram of penetrative lineation, 'b', for the Lac Couture area. (Contoured by the Schmidt method).



I. Contours 0-2.5-5.5-8-10.5 % per 1% area (76 points)



2. Contours 0-6.5-13-19.5-26% per 1% area (31 points)

Lac Couture Crater

Plate 2.

FIGURES

1. π-diagram of sheeting joints in zone 1.
   Contoured by the Mellis method.

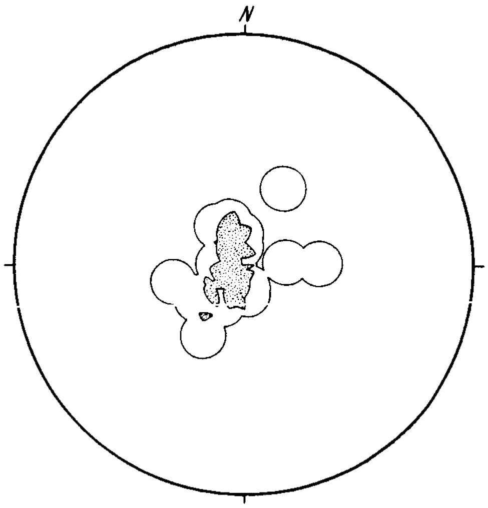
2. π-diagram of sheeting joints in zone 2.
   Contoured by the Mellis method.

3. π-diagram of sheeting joints in zones 3, 4, & 5.
   Contoured by the Mellis method.

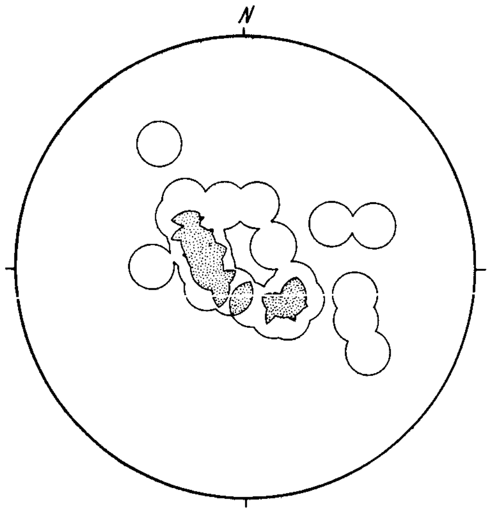
4. π-diagram of sheeting joints in zone 6.
   Contoured by the Mellis method.

5. π-diagram of sheeting joints in zones 1 & 2.
   Contoured by the Schmidt method.

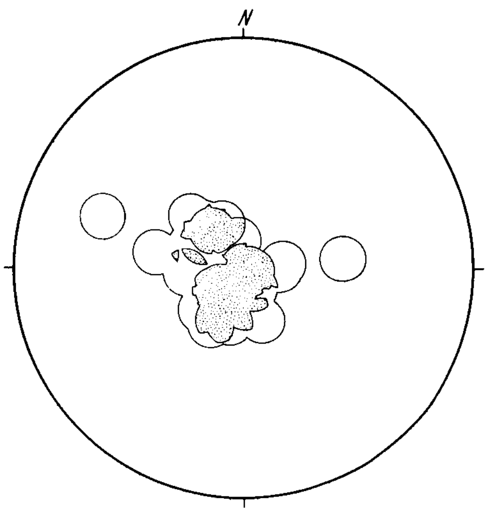
6. π-diagram of sheeting joints in zones 3, 4, 5, & 6.
   Contoured by the Schmidt method.



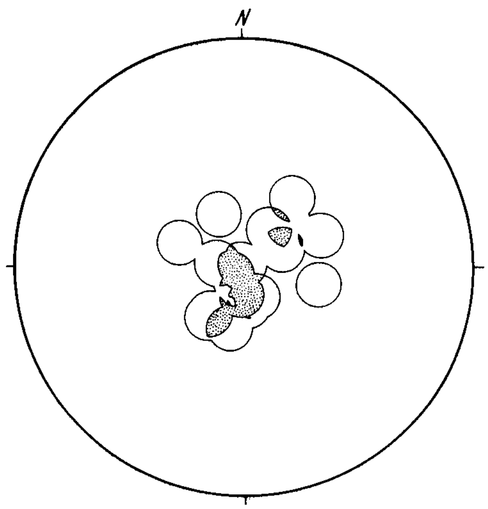
I. Contours 6 and 20 % per 1 % area (16 points)



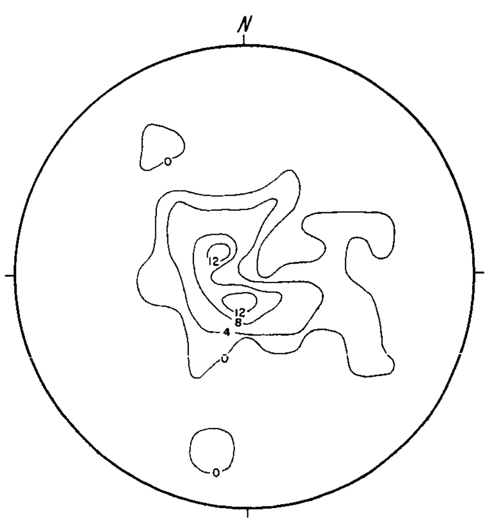
2. Contours 4 and 11 % per 1% area (26 points)



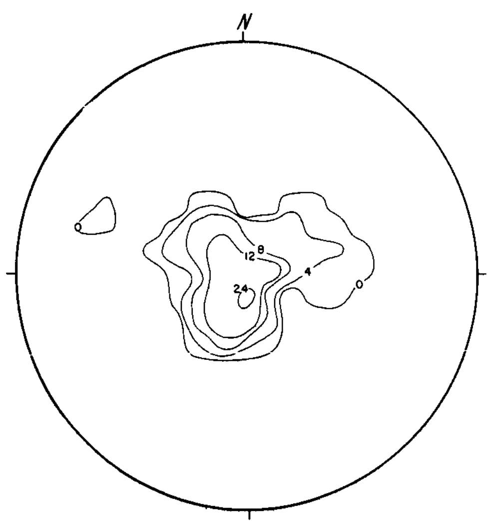
3. Contours 4 and 11 % per 1 % area (27 points)



4. Contours 6 and 20 % per 1 % area (17 points)



5. Contours 0-4-8-12 % per 1 % area (42 points)



6. Contours 0-4-8-24 % per 1% area (44 points)

the distribution of points is annular, which reflects a predominance of gently inclined sheeting joints on the mainland immediately surrounding the lake. A composite diagram of zones 3, 4, 5, & 6 (figure 6) indicates the horizontality of the sheeting planes and the lack of influence in these zones of any flexures associated with cratering. The annular distribution is preserved in the composite of zones 1 and 2 (figure 5).

Though positive conclusions are hampered by insufficient data, the results are compatible with expectations. The inclined sheeting joint planes of zone 2 may represent a fossil rim folds.

The attitudes of the subvertical joints are recorded in plates 3, 4, & 5. In order to pick out possible variations in the joint pattern between 'rim' rock and country rock, and to test for directional properties in smaller domains, the joint attitudes were plotted on a zonal (zones 1 & 2 combined; zones 3, 4, 5, & 6 combined) as well as a quadrant basis.

The best developed regional joint sets are deduced from the composite diagram (plate 5, figure 2) which includes zones 3, 4, 5, & 6 for all quadrants. These have the following orientations: 000°/vert, 030°/vert, 095°/vert, 115°/vert, and 150°/80° southwest. However, only the following persist in all quadrants 000-010°/vert, 030-050°/vert, 085-100°/vert, and 150-165°/vert. But few additional sets are developed in the rocks within the inner two zones, though their distribution is as a more complete girdle (cf. plate 5, figures 1 & 2). The maxima developed in the inner two zones, which are regarded as the limit of crater influence, coincide, when treated in their respective quadrants, to a radial set, a concentric set and a

Lac Couture Crater

Plate 3. π-diagrams of subvertical joints.
(Contoured by the Schmidt method).

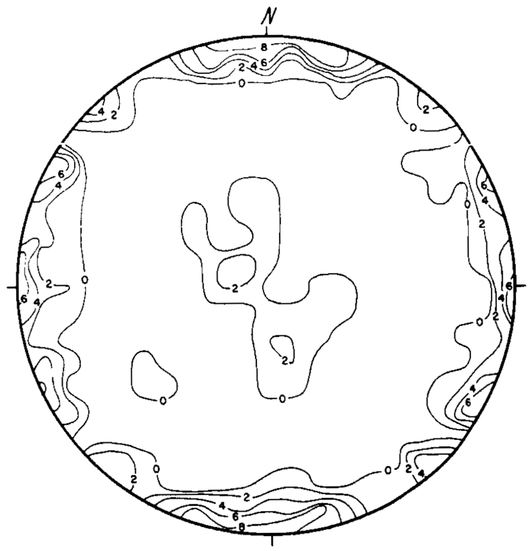
FIGURES

1a. North quadrant - zones 1 & 2.

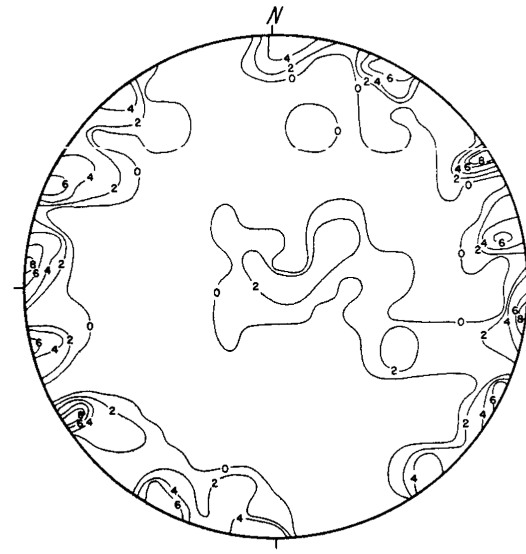
1b. North quadrant - zones 3, 4, 5 & 6.

2a. East quadrant - zones 1 & 2.

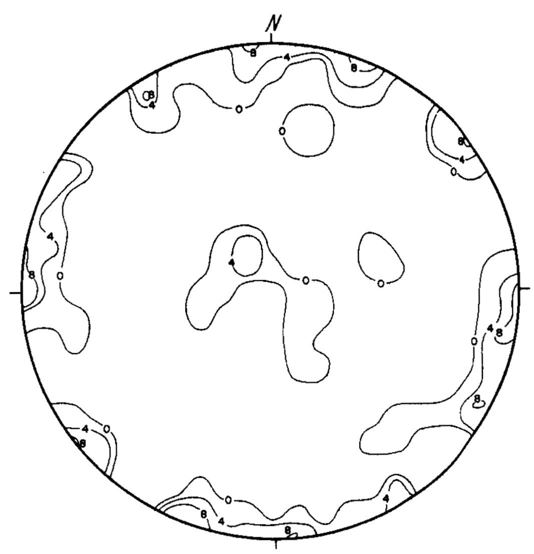
2b. East quadrant - zones 3, 4, 5 & 6.



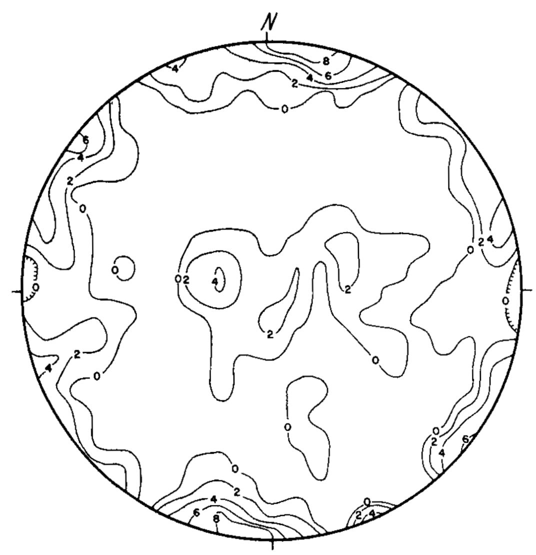
Ia. Contours 0-2-4-6-8 % per 1% area (83 points)



Ib. Contours 0-2-4-6-8 % per 1% area (57 points)



2a. Contours 0-4-8 % per 1% area (38 points)



2b. Contours 0-2-4-6-8 % per 1% area (97 points)

Lac Couture Crater

Plate 4. π-diagrams of subvertical joints.
(Contoured by the Schmidt method).

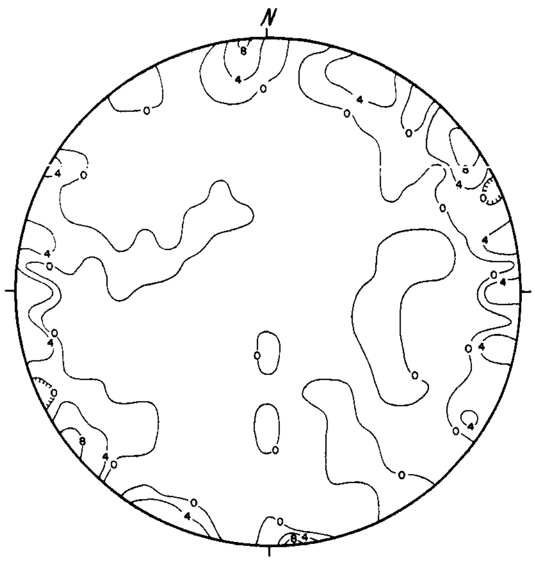
FIGURES

3a. South quadrant - zones 1 & 2.

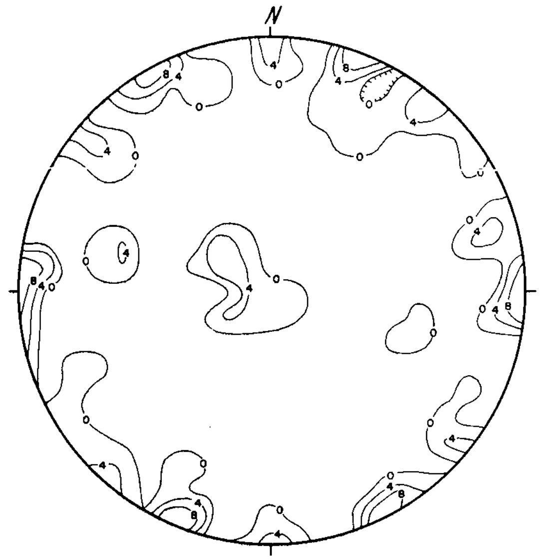
3b. South quadrant - zones 3, 4, 5 & 6.

4a. West quadrant - zones 1 & 2.

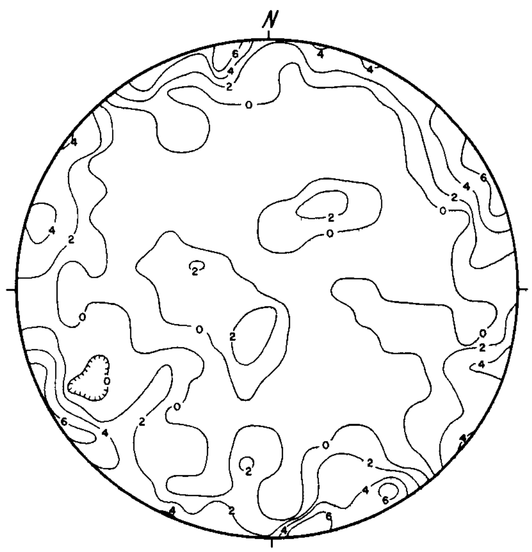
4b. West quadrant - zones 3, 4, 5 & 6.



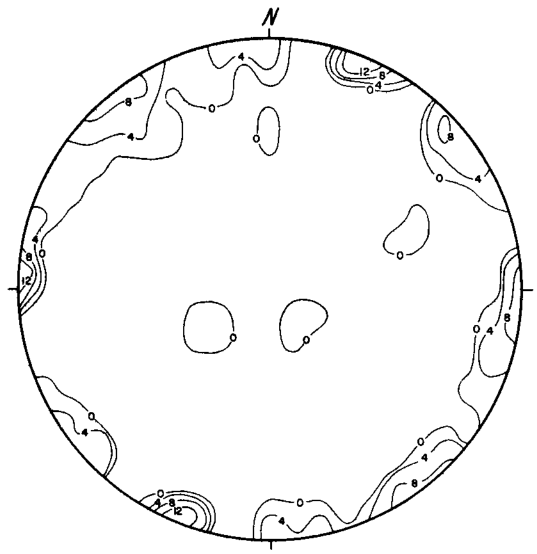
3a. Contours 0-4-8 % per 1% area (62 points)



3b. Contours 0-4-8 % per 1% area (50 points)



4a. Contours 0-2-4-6 % per 1% area (106 points)



4b. Contours 0-4-8-12 % per 1% area (47 points)

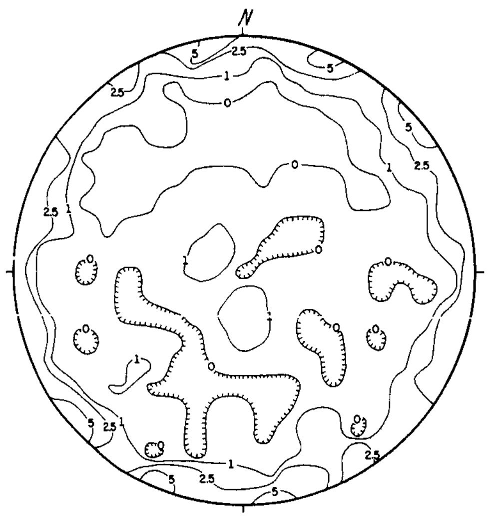
Lac Couture Crater

Plate 5. π-diagrams of subvertical joints.
(Contoured by the Schmidt method).

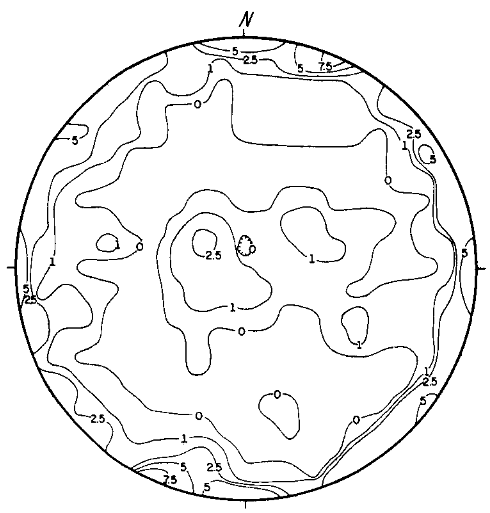
1. Composite plot for zones 1 & 2.

2. Composite plot for zones 3, 4, 5 & 6.

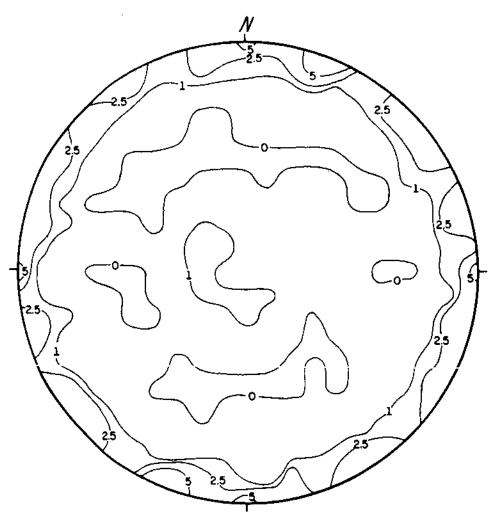
3. Composite plot of all zones.



I. Contours 0-1-2.5-5 % per 1% area (289 points)



2. Contours 0-1-2.5-5-7.5 % per 1% area (251 points)



3. Contours 0-1-2.5-5 % per 1% area (540 points)

conjugate set about the radial direction. This latter set may represent conjugate shear joints distributed circumferentially at about 30° to a radial line.

Conclusions:

1. By comparing spatial orientations of successive annular zones the influence of the superimposed structures can be delimited from the purely regional structures.

2. Preferred orientations are not as pronounced in the fabric of the inner zones as in the country rock.

TRICLINICITY OF POTASH FELDSPAR AROUND THE NEW QUEBEC CRATER

There exists in the potash feldspars, a continuous gradation from a monoclinic lattice to a triclinic lattice having angles $\alpha = 90^{o}39'$, and $\gamma = 87^{o}47'$. The latter are the largest departures from monoclinic symmetry thus far found, and a potash feldspar with these interaxial angles is termed "maximum microcline". The deviation from the monoclinic lattice, or triclinicity, may be used as a function of the degree of Al-Si ordering, with the triclinic lattice representing complete order, and the monoclinic lattice representing disorder.

The triclinicity or Δ is detected easily on x-ray diffraction patterns. For a triclinic lattice, there will be a separation between the peaks (hkl) and ($h\bar{k}l$), whereas for the monoclinic lattice, these peaks will coincide. The degree of triclinicity is reflected by the amount of this separation, relative to the maximum possible separation, expressed in terms of the difference in the 'd' spacings of two such peaks. The peaks (130)($1\bar{3}0$) and (131)($1\bar{3}1$) commonly are used. The latter peaks have a maximum possible difference in 'd' spacings of slightly under 0.08. This may be converted to a scale from 0 to 1 by multiplying the observed peak separation by a factor of 12.5.

Hence, $\Delta = 12.5\ (d_{131} - d_{1\bar{3}1})$.

The triclinicity of potash feldspar from the New Quebec crater and precints were determined, because a high intensity, short duration stress, as would be caused by a meteorite impact, might induce disordering of the lattice and a subsequent lowering of the triclinicity. The potash feldspar was separated by successively crushing, selectively staining (the K-feldspar), and hand picking under a binocular microscope. The clean samples were crushed and ground, then run on an x-ray diffractometer unit. The main difficulty was in finding sufficient potash feldspar in some of the specimens. The triclinicity varied from 0.88 to 0.97, with no observable variation outward from the rim.

In addition, two samples from the Brent crater were run, one sample being from the rim and the other at a distance of approximately 1-1/2 miles farther out. The rim sample had a triclinicity of 0.82; the other sample was monoclinic.

A METHOD OF SEPARATING POTASH FROM PLAGIOCLASE FELDSPARS IN GRANITIC ROCKS

This method for separating minerals of like physical properties (quartz, K-feldspar, and plagioclase) involves selective staining and hand picking. It is quicker, when small amounts only are needed (as for triclinicity and electron probe studies), than conventional methods using heavy liquid medii.

The following chemicals and equipment are necessary: fume hood; filter funnels (75mm); beakers (250 ml); Whatman's filter paper (No. 41, 11 cms); watch glasses; hydrofluoric acid; sodium cobaltnitrate solution - $Na_3(Co(NO_2)_6)$, (60 gms sodium cobaltnitrate to 100 ml water); barium chloride solution, $BaCl_2$, 5%; amaranth solution, 28.35 gms of F.D. & C. Red No. 2 (formerly amaranth) to 2 liters of water. Note: teflon equipment is preferred to glassware.

The rocks are crushed and the 0.25 to 0.5 mm range retained (generally, this ensures adequate separation of individual grains, while still keeping them to a reasonable size). The grains are placed on a piece of filter paper in a funnel, and etched with HF for 15 seconds under a fume hood. Wash 2 or 3 times with distilled water to remove HF. The potash feldspar is stained by adding sufficient sodium cobaltnitrate solution to cover the grains for from 1 to 2 minutes. The excess stain is removed by flushing gently a few times with distilled water, taking care not to wash off the stain. The barium chloride solution is then added for 15 seconds, and flushed once with distilled water. The amaranth solution is then added for 15 seconds, the excess being gently flushed off with distilled water. Allow grains to dry, either in a drying oven or in the open air. Note: it may be more convenient to remove the grains from the filter paper, and to do the flushing on a watch glass.

The dry grains may be hand-sorted easily under a binocular microscope, the potash feldspar being yellow and the plagioclase purple or red. Impure grains are distinguished easily.

THERMOLUMINESCENCE AND THE FEASIBILITY OF MEASURING STRESS INDUCED GLOW CURVES IN THE STUDY OF DEFORMATION AROUND CRATERS

History

The emission of light from stones has been known since as early as 400 B.C. However, it is not known whether this observation was of fluorescence, phosphorescence, thermoluminescence, or incandescence. The first recognition of thermoluminescence was in 1663, by Boyle, who observed the phenomenon in a diamond. The thermoluminescence of fluorite was discovered by Elsholtz in 1676.

Prior to 1950 a great deal of work was done on the thermoluminescence of rocks and minerals (as well as some artificial substances), with but few attempts to describe variations within a given geologic setting. The general conclusion (with many exceptions) from this period was that the intensity of the thermoluminescence was proportional to geologic age.

Since 1950 over 400 papers have been published on thermoluminescence. The ground-work for most of the recent papers is the report by Daniels and co-workers, who investigated quantitatively the many aspects of thermoluminescence on a U. S. Atomic Energy Commission project.

Theory

The phenomenon of thermoluminescence (liberation by rise in temperature of trapped electrons, whose transitions result in the emission of light), as well as other types of luminescence, is explained conveniently by the Bloch band theory of solids. According to this theory crystalline material contain a series of energy levels or bands. Electrons may move between these bands, which may be full (valence or ground state bands), or empty (conduction bands). Ideally, in a crystalline insulator, these bands consist of a series of 'permitted' energy levels, separated by 'forbidden' energy levels, and electrons cannot move across a forbidden level to an empty conduction band. However, due to various types of lattice defects, the energy levels are not in a perfect state, and some discrete permitted levels may form within the forbidden levels, as electron traps or as luminescent centers.

When an electron in a full band is excited by an external energy source, it can do one of three things; (a) move to a luminescent center and then return to a full band, (b) move to a conduction band, travelling through the lattice, and then return to a full band as before, or (c) it may be trapped and held in a lattice defect before reaching a conduction band. Additional energy (activation energy), usually heat, must then be added before the electron can be released to return to a full band as in (b). The additional energy imparted to the electron is released mainly as photons of light as the electron passes through the luminescent center. The first two of the above conditions illustrate the mechanisms of fluorescence, the third for both phosphorescence and thermoluminescence.

Some of the factors influencing the nature and type of thermoluminescence are as follows:

i) the amount of energy required to enable a lattice defect to function as a luminescent center is variable, and depends on various factors such as the type of lattice defect, and crystal structure.

ii) the amount of energy required to release a trapped electron is variable. A defect which requires only a small amount of energy is termed a shallow trap, whereas one requiring a large amount of energy is termed a deep trap. Intermediate traps lie in the range between shallow and deep traps.

iii) various types of lattice defects are possible, and include: point defects (missing atoms or ions, atoms or ions moved to interstitial positions, ions and cations exchanging positions, and introduction of foreign atoms or ions); line defects (screw or edge dislocations); planar defects (internal and external defect surfaces); and combinations of the above.

iv) the tendency for a lattice defect to act as an electron trap increases as the temperature decreases, which suggests that thermoluminescence is a low temperature form of fluorescence.

Measurement

The measurement of thermoluminescence is relatively simple. The sample is heated at a constant rate in a light-tight compartment. The light emitted is picked up by a photo-multiplier tube, the signal amplified and fed into a recorder, where light intensity is plotted against time and/or temperature to produce a glow curve. The number of peaks, peak heights, and temperature of the peaks may be measured, or individual peaks may be integrated to give a measure of the amount of emission. With special equipment the wave length of the light can be measured.

Application

Theoretically thermoluminescent studies around craters should yield information on (a) the temperature gradient outward from the crater, (b) the age of crater formation, and (c) a quantitative measure of the solid state deformation outward from the crater.

While neither of the first two aspects have been tested on craters, the work done on the rocks adjacent to igneous dikes is not encouraging. The effect of a high intensity, short duration stress, as would be caused by the impact of a meteorite, would either release many of the traps (where the rocks deformed by rupture) or create new traps (rocks deformed by dialiation, distortion or folding). The shock induced thermoluminescence would manifest itself either as, (a) enhanced peaks, (b) reduced peaks, (c) shifted peaks, or (d) new peaks.

Recent work by Roach, Johnson, McGrath and Spence (1961) showed the effect of impact on thermoluminescence to be measurable in artificial craters, formed by an armour piercing bullet in Yule marble. Subsequent work by Roach, Johnson, McGrath, and Sterrett (1962) on the rocks from Meteor Crater, Arizona, led to the conclusion that the total amount of thermoluminescence (area under the glow curve) decreases systematically with distance from the shock origin, and that in some rock types, strong shock causes the low temperature peak to have a greater amplitude than the high temperature peak. These results are essentially confirmed (Wilmarth, et al, 1961; Short, 1961) on craters formed by underground nuclear explosions.

The preliminary investigation of thermoluminescence of rocks from craters in granitic terrains is not encouraging. Samples from the Brent Crater were run, for this group, at Loyola College, Montreal by Dr. D. McDougall. The variations are unsystematic. Samples from the New Quebec Crater have been run by Roach at the Federal Center, in Denver, with mixed results.

Conclusions:

Although it is unlikely that a hypervelocity impact would have no affect on the thermoluminescence of rocks surrounding an impact crater in granitic terrain, the evidence gathered to date does not warrant any development work being undertaken, by this group, at this time. However, information will be gathered and processed, and any new developments will be considered.

PLANNING FOR THE NEXT SIX MONTH PERIOD

It is felt that consolidation of existing investigations should take precedence over the development of new aspects. Work on the following topics is scheduled:

1. Microfabric analysis (orientation of deformation planes and planes of fluid inclusions in quartz) on rocks from Brent, New Quebec, and Lac Couture craters. If the results warrant, the study will be extended to rocks from the central granite dome of Vredefort and for comparison to the volcanic crater of the Pretoria Salt Pan.
2. Trend surface studies using the 2V values of the potash feldspar. There was no systematic development of these surfaces at Lac Couture, but the New Quebec rocks should be tested before abandoning the technique.
3. Determine the composition and structural state of the low 2V potash feldspars, which have been found at both the Lac Couture and Brent craters.
4. Continue the triclinicity studies on New Quebec and Brent, and extend the study to the Vredefort and the Pretoria Salt Pan.
5. Measure the degree of undulose extincting of quartz in rocks from the New Quebec crater.
6. Continue with the petrographic description of the rocks from the New Quebec crater, and test the sheeting joints in the country rock for possible rim folds.
7. Continue the search for coesite and stishovite.
8. Preliminary thinking into models of crater mechanism.

REFERENCES

Chayes, F., 1952: Notes on the Staining of Potash Feldspar with Sodium Cobaltnitrate in Thin Section: Amer. Min. Vol. 37, p. 337-340.

Daniels, F., and Saunders, D. F., 1950: Thermoluminescence of Rocks: Science, Vol. 111, p. 462.

Daniels, F., Saunders, D. F., et al., 1951: The Thermoluminescence of Crystals: Final Rept. U.S.A.E.C., AECU-1583, 26 chapters.

Gold, D. P., 1965: Study of Structural and Mineralogical Significance of Meteorite Impact Sites, Including Mineral Paragenesis, High Pressure Polymorphs, Micro-fractures and Quartz Lamellae: 2nd Annual Rept. N.A.S.A.

Goldsmith, J. R., and Laves, F., 1954a: The Microcline-Sanidine Stability Relations: Geochim et Cosmochim Acta, Vol. 5, p. 1-19.

____________ 1954b: Potassium Feldspars Structurally Intermediate between Microcline and Sanidine: Geochim. et Cosmochim. Acta, Vol. 6, p. 100-118.

Harvey, E. N., 1957: A History of Luminescence: Amer. Philo. Soc., Philadelphia. 692 p.

Laniz, R. V., Stevens, R. E., and Norman, M. B., 1964: Staining of Plagioclase Feldspar and Minerals with F.D. and C. Red No. 2: U. S. Geol. Surv. Prof. Paper 501B p. B152-B153.

MacKenzie, W. S., 1954: The Orthoclase-Microcline Inversion: Min. Mag. Vol. 30, p. 354-366.

McDougall, D. J., 1965: Personal Communication on Thermoluminescence: Loyola College, Montreal.

Roach, C. H., 1965: Personal Communication on Thermoluminescence: Geological Survey, Federal Center, Denver.

Roach, C. H., Johnson, G. R., McGrath, J. G., and Spence, F. H., 1961: Effects of Impact on Thermoluminescence of Yule Marble: U. S. Geol. Surv. Prof. Paper 424C, p. C342-C346.

Roach, C. H., Johnson, G. R., McGrath, J. G., and Sterrett, T. S., 1962: Thermoluminescence Investigations at Meteor Crater, Arizona: U. S. Geol. Surv. Prof. Paper 450D, p. D98-D103.

Rosenblum, S., 1956: Improved Techniques for Staining Potash Feldspars: Amer. Min. Vol. 41, p. 662-664.

Short, N. M., 1961: Applications of Geology to Underground Nuclear Explosions: Geotimes, Vol. 6, No. 3, p. 18.

Turner, F. J., and Weiss, L. E., 1962: Structural Analysis of Metamorphic Tectonites: McGraw-Hill Book Co., Inc., New York. 545 p.

Wilmarth, V. R., Botinelly, T., and Wilcox, R. E., 1961: Alteration of Tuffs by Ranier Underground Nuclear Explosion, Nevada Test Site, Nye County, Nevada: U.S. Geol. Surv. Prof. Paper 400-B, p. B149-B151.

Appendix I

Structural Studies on the New Quebec and Lac Couture Craters, New Quebec, Canada

Abstract

New Quebec and Lac Couture craters, with diameters of 2 and 9 miles, are located respectively at 61°17'N, 73°42'W, and 60°08'N, 75°18'W. These circular structures are superimposed upon folded Precambrian quartzo-feldspathic gneisses. Structural analysis of the following structural elements - foliation, lineations, joints, and shear zones, is applied in the areas surrounding these craters. At New Quebec the attitude of the structural elements in the rim rock were compared with those of the country rock. Because Lac Couture has no topographic rim, the surrounding area was divided into annular zones each representing a radius increment of 1 mile. Spatial orientations were compared on a zonal basis.

At New Quebec sheeting joints - subhorizontal in the country rock - are inclined outwards in the rim. By rotating the sheeting joints into a horizontal attitude and the foliation, lineation, and shear zone attitudes by a corresponding amount, the scattered points of the rim zone diagrams are tightened to conform with the country rock attitudes, indicating that the sheeting joints and shear zones are pre-crater in origin.

At Lac Couture the sheeting joints are subhorizontal except for the second zone out, which shows an annular distribution of points suggestive of either a fossil rim or rim syncline. The conformity of foliation and lineation to the regional pattern, suggests it is a deeply eroded crater.

Sub-vertical joints are more abundant and homogeneous in their distribution close to these craters. They appear to be the most sensitive deformation feature attendent with cratering.

Appendix II

Deformation Lamellae from the Lac Couture Crater, Quebec

Abstract

The breccia, exposed as glacial erratics on the shores of the Lac Couture Crater, Quebec is apparently an impactite. Clastic quartz grains imbedded in the devitrified matrix contain deformation lamellae. Brownish inclusions and material unresolvable at 800 power magnification form the lamellae. The refractive index of this material is lower than n_w of quartz.

In 117 grains investigated, 63 possess two sets of lamellae, 9 have three sets, and 1 contains four sets. The angle between the c-axis of the host quartz grains and the pole to the lamellae ranges from 0° to 90°. The majority of angles, however, are between 20° and 25° with minor coincidences with the ξ, r, z, s, and x cleavage planes. In grains containing two or more sets of lamellae the majority of interplanar angles lie between 35° and 40°, with others ranging from 15° to 90°.

The trigonal symmetry of low quartz requires the angle between rational planes of a form, whose $c \wedge \perp$ angle is approximately 23°, to be about 40°. The $c \wedge \perp$ angle of $\{10\bar{1}3\}$, a rare quartz cleavage, is $22^{\circ}56'$, and the interplanar angle between companion faces is $39^{\circ}28'17''$. The geometric coincidence between deformation lamellae and cleavage directions in quartz is demonstrated.

Similar planes are inclined at approximately 30° to the (010) twin composition plane in clastic plagioclase grains. Two sets intersect at about 60° in alternate twin lamellae.

The orientation of deformation lamellae in quartz is apparently partially crystallographically controlled, and perhaps partially influenced by a directed stress.